

**Final Technical Report**

**Shock Wave Dynamics in Weakly Ionized Plasmas**

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**Submitted by**

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## Overview

An experimental study of the dynamics of acoustic shock waves in weakly ionized gases has been performed. The measurements were performed using a pressure-ruptured shock tube. We report here the response of an argon glow discharge plasma to weak (non-ionizing) shock waves of Mach number in the range 1.5 - 3. Our results show that there is an increase in the velocity of a shock wave when it makes a transition from a neutral gas to a weakly ionized plasma. The observations also indicate that the shock acceleration cannot be accounted for by thermal effects only. The use of a turbulence model based on reduced kinetic theory suggests a role for turbulence in plasma-induced hypersonic drag reduction. The implications of these results for plasma-based drag reduction are discussed. This is the final technical report on NAG1-<sup>2114</sup>~~1930~~, NASA Langley Support for Shock Wave Dynamics in Weakly Ionized Plasmas to Florida A&M University.

## Introduction

There has been a recent increased interest in the interaction of shock waves with weakly ionized, non-equilibrium media. This is due to a potential application to the reduction of drag forces on hypersonic flight at high altitude through a decrease in the strength of the bow shock. Previous investigators<sup>1</sup> have suggested that for weakly ionized gases, an increase in the shock wave velocity and a corresponding decrease in shock amplitude can result compared to the unionized case. The decreased shock amplitude presents a means of improving the flight characteristics at high altitude by weakly ionizing the gas through which the flight occurs. The decreased shock strength in this medium then offers a substantial potential influence on the drag forces on the vehicle.

The anomalous dynamics of shock waves in weakly ionized plasmas have been studied experimentally in both non-equilibrium molecular gases (such as air and nitrogen) and monatomic gases such as argon and xenon.<sup>2</sup> In these experiments a glow discharge plasma formed in gases at a pressure of 15 - 30 torr was used. The plasma electron temperature was typically a few eV and the degree of ionization of the order of  $10^{-6}$  -  $10^{-5}$ . In some cases, a magnetic field was applied either longitudinal or transverse to the direction of the shock wave in order to study the role of the charged species on shock dynamics. The results of these experiments revealed similar features. Anomalous high shock velocities were observed in the plasma medium, together with a significant dispersion and weakening of the shock wave. In

the experiments with the magnetic field, it was reported that whereas longitudinal fields did not have any effect on the shock speed in the plasma, transverse fields caused the shock to slow to velocities similar to the neutral gas values.

Several possible mechanisms of shock acceleration have been suggested, including excitation of ion sound waves in the non-isothermal plasma and exothermal processes (such as anomalous relaxation) behind the shock wave front.<sup>3</sup> At the present time, however, there is no coherent model to explain all the observations.

We present here the results of a series of experiments looking primarily at the acceleration of shock waves in weakly ionized argon plasmas. A glow discharge plasma was used in this study, with an electron density,  $n_e$ , of  $10^{10}$   $\text{cm}^{-3}$ , neutral density,  $n_0 \sim 10^{16}$   $\text{cm}^{-3}$ , and electron temperature,  $T_e \sim 1 - 3$  eV. The pre-plasma shock speeds ranged from about 500 m/s to 950 m/s. The objective of this study was to characterize the dynamics of shock waves in weakly ionized plasmas in order to identify regimes of shock velocity enhancement and strength reduction that are relevant to aviation technology.

### Experimental Apparatus

A schematic of the experimental apparatus is shown in Fig. 1. A shock wave is initiated by rupturing a diaphragm separating the high-pressure and low-pressure sections of a shock tube. The low-pressure section consists of a 5" inner diameter shock development section and a 3" diameter test section.

The test section is made up of three 12" long modular quartz tubes, with installed *Kistler* 606A piezoelectric pressure transducers for monitoring the shock wave. The shock signals are displayed on fast digitizing, 784 Tektronix oscilloscopes. A glow discharge plasma, maintained by a DC high voltage, constant current source (<200 mA, 2 kV), is located in the central quartz tube and uses hollow molybdenum electrodes. The progress of the shock can thus be observed before, during and after the plasma. The gas pressure in the test section is maintained constant by a continuous flow of gas through the discharge.

The degree of ionization of the plasma,  $\alpha = n_i/n_0$  can be controlled by varying the mean discharge current density. The plasma gas temperature is monitored with a *chromega/alomega* thermocouple junction situated \*\* mm from the positive electrode. Two electric probes each with a 1 mm diameter, 1 mm long probe tip located in the middle of the plasma section are used to measure plasma properties such as electron number density,  $n_e$  and electron temperature,  $T_e$ . Optical spectral radiation from the plasma is observed with a diffraction grating monochromator and photomultiplier station. The spectral measurements provide information on the ionization state of the plasma as well as the emission characteristics of the plasma during the passage of the shock. Using these diagnostics the effect of the plasma on the shock wave could be characterized as a function of the plasma properties  $n_0$ ,  $n_e$ ,  $T_e$ ,  $n_i/n_0$  and shock Mach number.

## Experiments and Results

The experiments were performed over a range of shock Mach numbers from 1.5 to 3.0, using a test section pressure of either 1 Torr or 4 Torr argon. (The highest pressure at which the discharge could be sustained was  $\sim 4.5$  torr). The discharge current was typically  $\sim 100$  mA, using a voltage of about 1 kV across the electrodes. After initiation, the plasma was allowed to stand for about two minutes to reach a quasi-steady state before the shock wave was generated. This time period was arrived at after an observation of the thermocouple readings over a period of several minutes. A number of experiments were performed with and without the plasma under identical conditions. In all cases the propagation of the shock was monitored from the time it was generated until it was reflected from the end-wall. The average speeds of the shock wave in the neutral gas and in the plasma were obtained to an accuracy better than 5% from the pressure jump of the transducer signals. When the plasma was used, the discharge current during the transit of the shock was measured using a potential divider connected to one of the channels of the oscilloscopes. A typical set of signals from the oscilloscope is displayed in Fig. 2.

The pre-shock plasma current and optical emission signals obtained from the photomultiplier show that the plasma was quenched by the interaction with the shock. This quenching was attributed to the interruption of the discharge current resulting from the sustained recombination that occurred when the shock passed through the plasma. The plasma decay time was characterized by the e-folding time of the discharge current signals.

Observations showed that for pre-plasma shock speeds of up to  $\sim 850$  m/s, (i.e.  $\sim$ Mach 2.7) the transit time in the plasma tube was less than the existence time of the 1 torr plasma. This suggests that between the shock detecting transducers on the plasma tube, the shock wave interacted fully with a weakly ionized plasma. The decay times were observed to be shorter for the 4 torr plasmas, on the order of 70 microseconds, compared with transit times of about 200 microseconds within the plasma tube.

The plasma electron number density and electron temperature  $T_e$  were measured using either a single electrostatic (Langmuir) probe or the double electrostatic probe method.<sup>4</sup> The measurements were performed near the mid-point of the positive column of the glow discharge. The results were as follows:  $n_e \sim 7.5 \times 10^{10} \text{ cm}^{-3}$ ,  $T_e = 3$  eV for the 1 torr plasma;  $n_e = 1 \times 10^{10} \text{ cm}^{-3}$ ,  $T_e = 1.5$  eV, for the 4 torr plasma. A study of the plasma radiation spectrum from  $3000 \text{ \AA} - 7000 \text{ \AA}$  indicated that the plasma was predominantly singly ionized. This is in agreement with the results of the plasma density and temperature measurements. The degree of ionization of the plasma,  $\alpha$ , is therefore of the order of  $10^{-6}$ . The plasma gas temperature which was measured with the thermocouple, peaked at  $\sim 330$  °K on the axis for the 1 torr discharge, falling to  $\sim 310$  °K at a radius of 1" from the axis. At 4 torr, the plasma was observed to have a somewhat hollow structure near the positive electrode. In this case, the observed temperature on the axis was 330 °K, dropping to 325 °K at a radius of 1".

In Fig. 3, the results of observations of shock speeds are given for 1 torr and 4 torr argon over a range of Mach numbers. In both cases, compared to the unionized gas, there is a significant increase in the shock speed when the shock wave makes a transition from the neutral gas to the weakly ionized plasma. The percentage increase in shock speed is higher for lower Mach numbers. At Mach  $2.0 \pm 0.2$ , the average percentage increase in the pre-plasma shock speed is about 14 % for 1 torr plasma and 20 % for 4 torr. The largest increase for the measurements reported here was obtained at ~33 % in 4 torr plasma.

The increase in shock speed did not correlate in any way with the temperature measured with the thermocouple for either 1 torr or 4 torr argon. There was also no observed dependence on the discharge current. In fact the results in Fig. 3 were all obtained with a current of  $100 \pm 5$  mA. It was not possible, using the current apparatus, to change the magnitude of the plasma discharge current by a large factor in order to observe a dependence on current.

### Discussion

The thermal sound speed in argon at 330 °K is  $c_s = 328$  m/s. This corresponds to a 5% increase in the acoustic speed over the room temperature value. The observed average shock speeds in the weakly ionized plasma exceed this thermal value by about 10 % or 15% for the 1 torr and 4 torr argon plasmas, respectively. It is evident, therefore, that within the parameter range of the experiments reported here, other mechanisms influence the



propagation of the shock wave within the plasma. The observed decrease in acceleration at increasing Mach numbers, evident in Fig. 3, may be attributed to a faster quenching of the plasma by the stronger shock. For example for the 1 torr plasma, the time to decay to 63% of peak current on interacting with a Mach 1.5 shock is ~450 microseconds. At Mach 2.8, it is about 150 microseconds.

The average shock accelerations observed in this study are less than the values reported by previous investigators. For example, Klimov et al. (see ref. 1) reported shock accelerations from 500 -800 m/s to 1200 - 1300 m/s, an increase of 50% - 140%, for shock waves generated in air. It should be noted, however, that those experiments were conducted at higher current densities, >15 mA, cm<sup>2</sup>, in plasmas at higher pressures, ~10 - 30 torr.

Many hypotheses have been proposed to explain the anomalous dynamics of shock waves in plasmas. In experiments conducted in molecular gases, it has been suggested that inelastic collisions between plasma electrons and molecules may result in non-equilibrium "trapping" of vibrational energy.<sup>5</sup> This stored energy, when released behind the shock, could result in the observed shock dynamics. In the current experiments, it is difficult to envisage such significant energy trapping in argon excitation that can possibly account for the observed shock acceleration. Also a "vibrational/translational" relaxation even in polyatomic gases cannot account for the observed influence of a transverse magnetic field as reported by Garshkov et al. (see ref. 2

Another mechanism attributes the formation of an electrical double layer observed in certain experiments to a high electron mobility and electron density gradients in the shock wave.<sup>6</sup> (Also see ref. 3.) This results in electron diffusion relative to ions, leading to an electric potential jump in the shock wave front. The large velocity results in an increase in the electron density ahead of the shock and may lead to a thermal precursor. The increased shock velocity and reduction in amplitude can then be explained due to gas heating by this precursor.

A third model assumes that a mechanism operates to convert some of the energy in an incident shock wave into kinetic energy of the neutral particles ahead of the shock front.<sup>7</sup> This energy transfer may be implemented by ion acoustic waves excited by the shock front. The appearance and rapid damping of these ion waves would give rise to a thermal precursor ahead of the shock front with the result that the neutral particles gain kinetic energy and the velocity of the shock wave in the plasma increases. (The ion acoustic speed is

$$v_s = \sqrt{\frac{kT_e + \gamma kT_i}{M_i}}, \text{ much higher than the neutral sound speed). In the}$$

experiments reported here  $v_s$  is estimated to be over 1500 m/s for a plasma temperature of 1 eV. There is, therefore, the possibility of ion sound waves being involved in the shock acceleration process.

Using reduced kinetic theory,<sup>8</sup> turbulent processes with correlation time scales comparable to that of a nonequilibrium process may distort the natural evolution of the nonequilibrium process.<sup>9</sup> The distortion has been observed

in  $\text{NO}_2$  recombinations<sup>10</sup>, in polymer mixing,<sup>11</sup> in detonation waves,<sup>12</sup> and in heterogeneous nucleation.<sup>13</sup> In most cases just cited, the indication of turbulent distortion came in the form of a dependence of a turbulence sensitive parameter (droplet size, detonation reactant, etc.) on Reynolds number showing an Orr-Sommerfeld-like relationship<sup>14</sup> parameterized by a dimensionless characteristic frequency. Distortions in nonequilibrium processes can be manifest in the effective local speed of sound.<sup>15</sup> If plasma-induced drag reduction, resulting from a manipulation of the local speed of sound, is to be a turbulence sensitive parameter, then there may be a similar dependence of drag reduction on Reynolds number.

Since we know the local density, the local speed, and the local viscosity, we can determine the unit Reynolds number ( $\text{Re}/l$ ) in all of our data. Averaging the data in Figure 3 for the region  $M > 2$ , we show in Fig. 4 the difference in shock wave speed between plasma and non-plasma flow versus ( $\text{Re}/l$ ) for our measurements. There is an onset of Reynolds number-based influence on shock wave speed at roughly  $(\text{Re}/l) = 8 \times 10^4$ . The overall shape of the dependence is consistent with the predictions in reference 14. Furthermore, if we use as a large scale correlation length the diameter of the shock tube, the analysis in reference 7 predicts a turbulent characteristic frequency (for a peak Reynolds number of  $> 22 \times 10^4$ ) of  $> 3 \text{ kHz}$ . Overall, these results are at least qualitatively consistent with an important role for turbulence in drag reduction in hypersonic flow using weakly ionized gases.

In order to isolate the mechanism(s) responsible for the observed shock dynamics, further experimentation over a wider plasma parameter range is necessary. Also, the analytic problem of electron density profiles in the vicinity of the shock front in the plasma must be studied in order to make predictions of possible electron diffusion across the shock front and hence energy transfer to upstream plasma particles which can result in gas heating. This mechanism may then be compared with one that involves plasma ions through the propagation of ion-acoustic waves.

### Summary

An investigation of the dynamics of shock waves in weakly ionized argon plasmas has been performed using a pressure ruptured shock tube. The velocity of the shock is observed to increase when the shock traverses the plasma. The observed increases cannot be accounted for by thermal effects alone. Possible mechanisms that could explain the anomalous behavior include a vibrational/translational relaxation in the nonequilibrium plasma, electron diffusion across the shock front resulting from high electron mobility, and the propagation of ion-acoustic waves generated at the shock front. Using a turbulence model based on reduced kinetic theory, analysis of the observed results suggest a role for turbulence in anomalous shock dynamics in weakly ionized media and plasma-induced hypersonic drag reduction.

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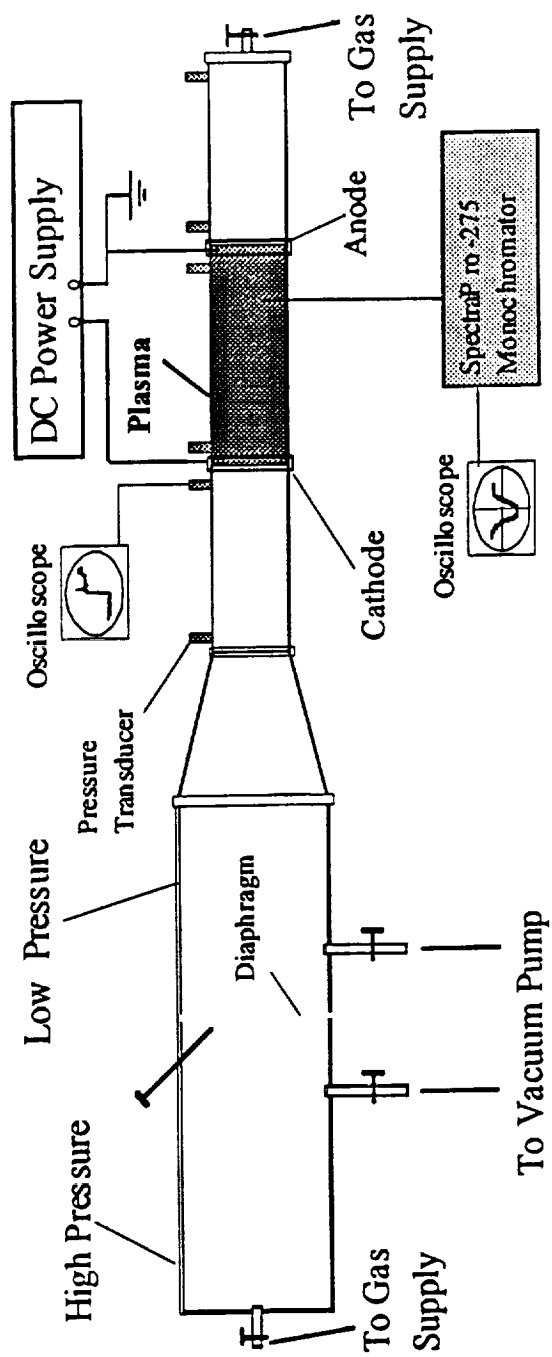


FIGURE 1

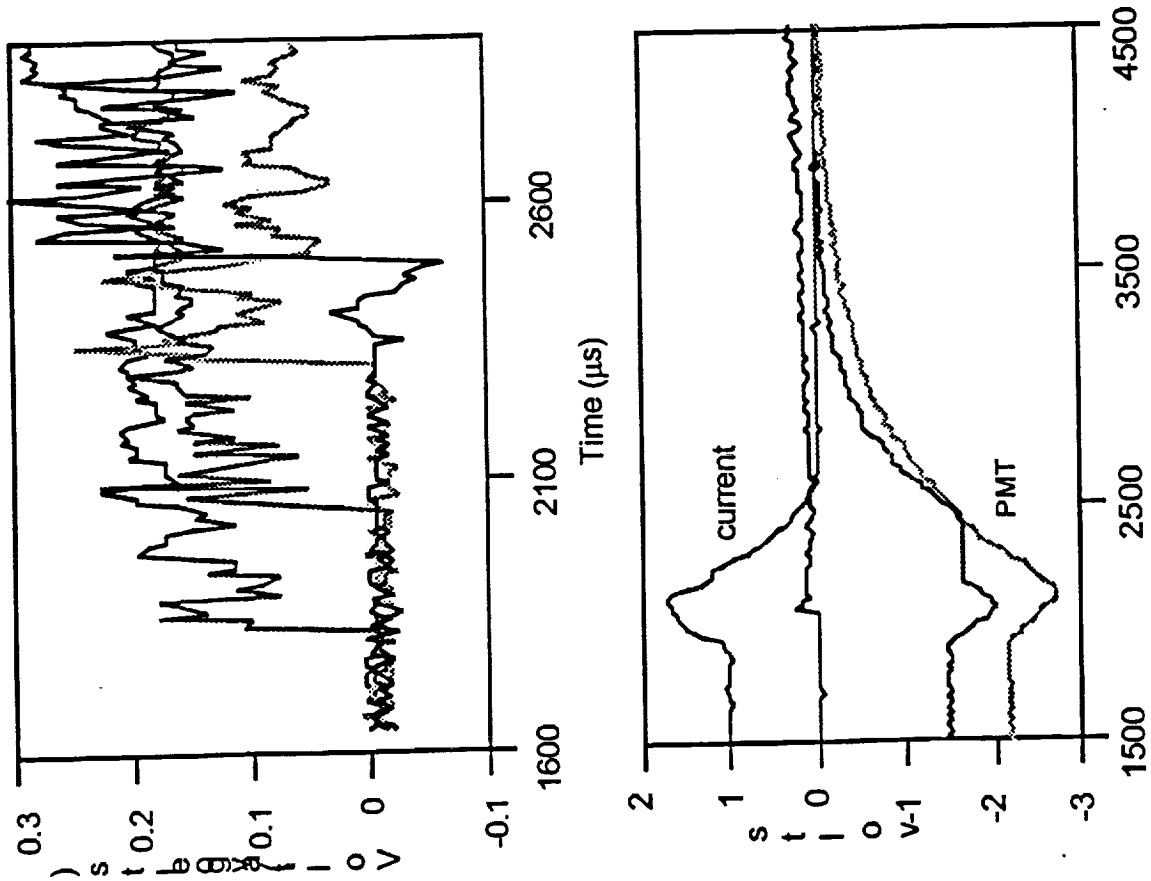


FIGURE 2

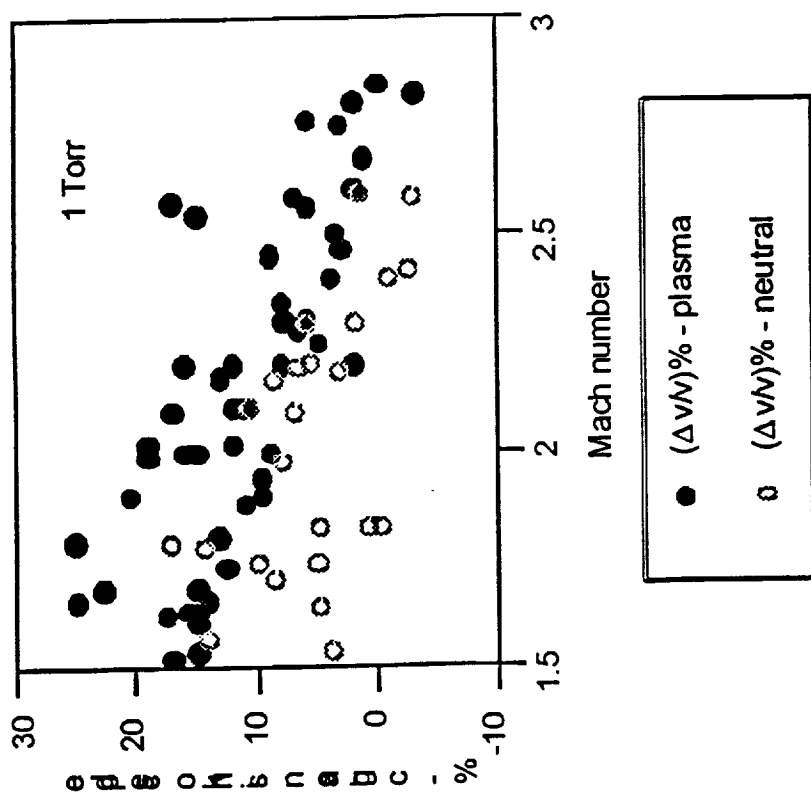


FIGURE 3

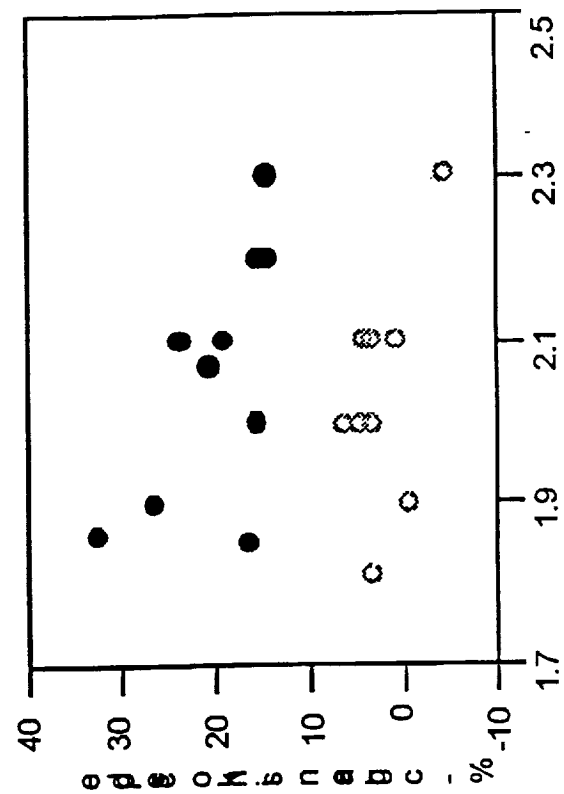




FIGURE 4

